

Vision

By 2025, develop (1) the technology to implement ocean sequestration of CO₂, (2) the knowledge to understand its effects on marine ecosystems and on the ocean's biogeochemical cycles, and (3) the modeling tools to determine the long-term fate of sequestered CO₂.

3 OCEAN SEQUESTRATION

The ocean represents a large potential sink for sequestration of anthropogenic CO₂ emissions. Although the long-term effectiveness and potential side effects of using the oceans in this way are unknown, two methods of enhancing sequestration have been proposed:

- the direct injection of a relatively pure CO₂ stream that has been generated, for example, at a power plant or from an industrial process (see Sect. 3.1)
- the enhancement of the net oceanic uptake from the atmosphere, for example, through iron fertilization (see Sect. 3.2)

Other pathways are also possible but may require longer time frames to be developed (see Sect. 3.3). For a given pathway, our goal is to analyze the tradeoffs among cost, long-term effectiveness, and changes to the ocean ecosystem.

On average, the ocean is about 4000 m deep and contains 40,000 GtC (IPCC 1996). It is made up of a surface layer (nominally 100 m thick, but the depth varies), a thermocline (down to about 1000 m deep) that is stably stratified, and the deep ocean below 1000 m. Its waters circulate between surface and deep layers on varying time scales from 250 years in the Atlantic Ocean to 1000 years for parts of the Pacific Ocean. The amount of carbon that would cause a doubling of the atmospheric concentration would change the deep ocean concentration by less than 2%.

Currently, net oceanic uptake of 2 ± 0.8 GtC/year¹ results from the increase in

¹This number for net ocean uptake is from IPCC and is based on data for the mid-1980s. Changes in sea-air forcing since then should have increased this flux slightly.

anthropogenic CO₂ in the atmosphere. On a time scale of 1000 years, about 85% of today's anthropogenic emissions of CO₂ will be transferred to the ocean (see Fig. 3.1). Ocean sequestration strategies attempt to speed up this process to reduce both peak atmospheric CO₂ concentrations and their rate of increase.

Although the ocean's biomass represents about 0.05% of the terrestrial ecosystem, it converts about as much inorganic carbon to organic matter (about 50 GtC/year) as do processes on land. The photosynthetic fixation of CO₂ by ocean organisms, followed by the sinking and slow remineralization (conversion to CO₂) of organic carbon, is a natural process for sequestering CO₂ in the deep sea. This process is often referred to as the "biological pump" (see Fig. 3.2).

The question is whether we can use the deep sea as a site for sequestration of additional anthropogenic CO₂. Many people are wary of ocean sequestration, including some authors of this chapter, because it is known that small changes in biogeochemical cycles may have large consequences, many of which are secondary and difficult to predict. Nevertheless, ocean carbon sequestration is occurring on a large scale today, and entrepreneurs are already trying to commercialize these technologies. Therefore, it is imperative to conduct research to better understand the risks as well as the opportunities. The ocean plays an important role in sustaining the biosphere, so any change in ocean

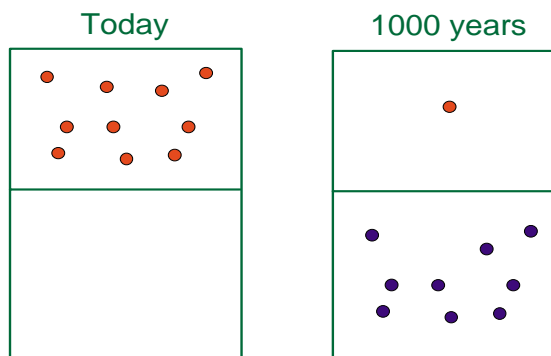


Fig. 3.1. Every year the ocean actively takes up one-third of our anthropogenic CO₂ emissions. Eventually (over 1000 years), about 85% of today's anthropogenic emissions of CO₂ will be transferred to the ocean. Ocean sequestration strategies attempt to speed up this ongoing process to reduce both peak atmospheric CO₂ concentrations and their rate of increase.

ecosystem function must be viewed with extreme caution.

How much carbon can the ocean sequester? Because of high pressures prevailing in deep ocean environments, a large quantity of CO₂ (exceeding the estimated available fossil fuel resources of 5,000 to 10,000 GtC) may be dissolved in deep ocean waters. However, a more realistic criterion needs to be based on an understanding of the biogeochemistry of the oceans. At present, we do not have enough information to estimate how much carbon can be sequestered without perturbing marine ecosystem structure and function; obtaining this information is one of the goals of the proposed research (Takahashi et al. 1981; Sarmiento and Bender 1994).²

²As an example calculation with no implications as to what an environmentally acceptable amount is, adding about 1300 GtC to the ocean would result in a pH decrease of 0.3. This pH change is similar to the change that will occur in the surface ocean as a result of doubling the preindustrial amount of atmospheric CO₂. The change in surface seawater pH today, from that of preindustrial times, is already 0.1.

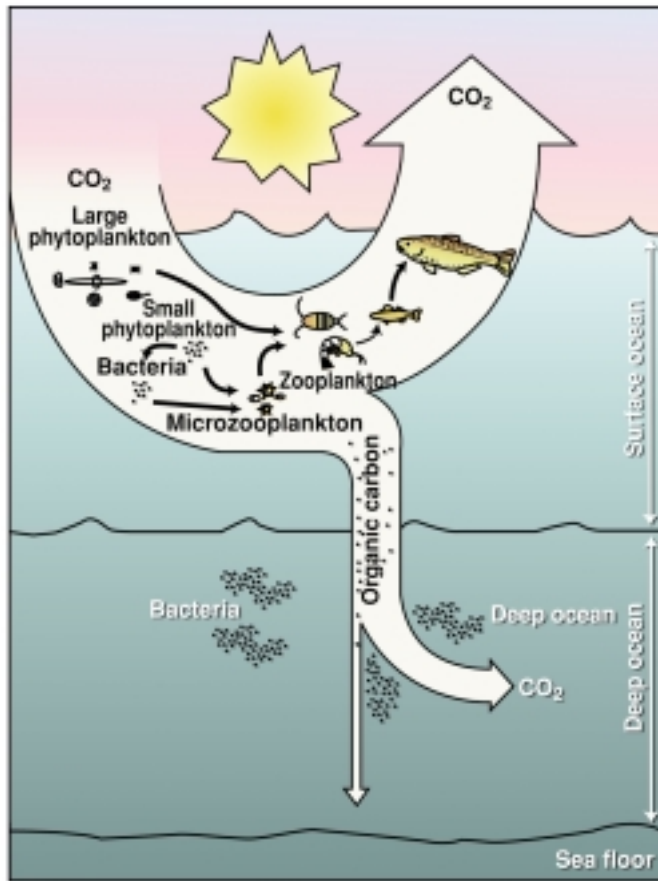


Fig. 3.2. A schematic diagram of the biological pump. In this generalized pelagic food web, CO₂ is being fixed by phytoplankton through photosynthesis. Phytoplankton are consumed by zooplankton that may, in turn, be consumed by higher trophic organisms, such as fish. Organic carbon in the form of detritus (e.g., fecal pellets, decaying organisms) sinks to the ocean depths, where it is remineralized to CO₂ by bacteria en route.

3.1 DIRECT INJECTION OF CO₂

The direct injection of CO₂ into the ocean requires starting with a fairly concentrated stream of CO₂ and delivering it to locations in the ocean where it will be effectively sequestered for hundreds of years, if not longer. To accomplish this, CO₂ would likely be injected as a liquid below the thermocline at depths greater than 1000 m (Herzog 1998). One limitation of this approach is that it is best suited to large, stationary CO₂ sources with

access to deep-sea sequestration sites—sources that may account for about 15 to 20% of our anthropogenic CO₂ emissions.

We have the technology to proceed with this option. However, we do not have the knowledge to adequately optimize the costs, determine the effectiveness of the sequestration (i.e., its impact in mitigating climate change), and understand the resulting changes in the biogeochemical cycles of the oceans. This section addresses how we may gain this knowledge.

3.1.1 Science and Technology Requirements

There are many technical options for sequestration by direct injection of CO₂. For example, injections may occur at moderate depths (1000–2000 m), at deep depths (>3000 m), in depressions on the ocean floor, or even into the suboceanic crust of the earth. The CO₂ may be sequestered by dissolution in the water column or by the formation of CO₂ hydrates, which are solid, ice-like compounds. The delivery of the CO₂ may be by pipeline or tanker. In all cases, on the scale of kilometers around the injection point, near-field computer models are needed to understand the physical and chemical interactions between CO₂ and seawater and the interaction between CO₂-enriched seawater and stratified surrounding water. One challenge is to determine how to use the buffering effect of bottom sediments (e.g., the ability of calcium carbonate to react with the CO₂) to increase the capacity

and effectiveness of ocean sequestration (Archer 1996). Another challenge is to understand the kinetics associated with the formation of CO₂ hydrates and to try to take advantage of their properties (e.g., increased density, lower mass transfer coefficient) for carbon sequestration. Finally, engineering analysis is required to estimate the costs of the various injection pathways.

Sequestration effectiveness will depend on the exact depth and location of the injection. In general, the deeper the CO₂ is injected, the more effectively it is sequestered; but injecting deeper requires more advanced technologies and may increase costs. Regional and global ocean general circulation models (OGCMs) are required to quantify sequestration effectiveness by calculating the reduction in atmospheric CO₂ as a function of time as a result of various ocean sequestration strategies. However, OGCMs must be improved to reduce the uncertainty associated with their results.

Environmental impacts near the injection point must be detailed, and the long-term, broad-scale impacts on the function of the ocean ecosystem must be understood. The most significant environmental impact is expected to be associated with lowered pH as a result of the reaction of CO₂ with seawater, although there could also be direct impact from the CO₂ itself. Non-swimming marine organisms residing at depths of about 1000 m or greater are most likely to be affected adversely by more acidic seawater; the magnitude of the impact will depend on both the level of pH change and the duration of exposure. The microbial community would also be affected, causing unknown impacts

on biogeochemical processes that play a crucial role in the ocean carbon cycle. Local environmental impacts may be minimized by designing the injection system to disperse the CO₂. Specific needs for R&D include gathering baseline data and implementing cost-effective monitoring. Robust, predictive models could help reduce the costs of monitoring by focusing sampling on areas of greatest potential impact.

3.1.2 Current Scientific and Technological Capabilities

Led by offshore exploration and production activities of the oil and gas industry, great strides have been made in the development of undersea offshore technology. It is becoming routine to work in depths approaching 2000 m. Work at much deeper depths, even approaching 10,000 m, is possible at reduced scales and/or time horizons, as has been shown in deep drilling and other scientific programs. However, many technical challenges still exist in going deep at large scales for extended times. Therefore, as a first step, it appears that the best strategy is to discharge the CO₂ below the thermocline at moderate depths of 1000 to 2000 m.

To implement that strategy, several methods of injection have been proposed (Fig. 3.3). One method is to transport the liquid CO₂ from shore in a pipeline and to discharge it from a manifold lying on the ocean bottom, forming a rising droplet plume. Another method is to transport the liquid CO₂ by tanker and then discharge it from a pipe towed by the moving ship. Although the means of delivery are different, the plumes resulting from these two options would be quite similar and, therefore, research on these two injection

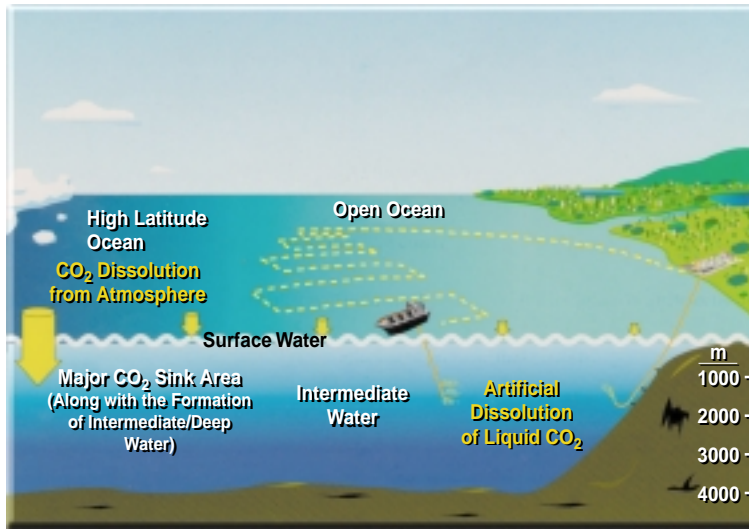


Fig. 3.3. For injection of CO₂ at depths of 1000 to 2000 m, it has been suggested that liquid CO₂ be transported from shore through a pipeline for discharge from a manifold lying on the ocean bottom. Another proposal is to transport the liquid CO₂ by tanker and then discharge it from a pipe towed by the moving ship.

methods should be considered complementary.

Once the CO₂ leaves the pipe, our current capabilities are much more limited. Models do exist to characterize the near-field plume, but they have not been validated with experimental data. We know that CO₂ hydrates may be formed from the injected CO₂ (see the sidebar on formation of CO₂ hydrates). The thermodynamic behavior of hydrates is well understood and their kinetics have been extensively investigated. However, we do not fully understand the kinetics that will control the formation and dissolution of hydrates in seawater, especially under the dynamic conditions in the plume.

Regional and global OGCMs are available to describe the ultimate fate of the injected CO₂ by modeling its behavior in the mid-field (tens to hundreds of kilometers from the injection point) and in the far field

(hundreds of kilometers and greater from the injection point) (Fig. 3.4). These models can simulate broad characteristics of observed transient tracer fields (e.g., chlorofluorocarbons, carbon-14, and tritium), whose movements can be detected in the open ocean. However, for modeling the fate of a point source such as injected CO₂, the uncertainties are large and the results will not be definitive.

Perhaps the area we are least capable of understanding is the environmental consequences of

CO₂ injection. We do understand the ocean's capacity to neutralize the water that is acidified by injected CO₂. We have models to predict pH changes to tens of kilometers around the injection point. However, we have very little knowledge of how the pH change or other impacts due to CO₂ injection would affect the biogeochemistry and ecosystems in the deep ocean.

These are selected research activities now under way to evaluate the ocean sequestration of CO₂.

International Field Experiment. Is ocean sequestration of CO₂ technically feasible? What are its environmental impacts? Can these impacts be minimized economically? An international research project is addressing these questions. Japan, Norway, and the United States signed a Project Agreement for International Collaboration on CO₂ Ocean Sequestration in December 1997; since that time, Canada, Australia, and

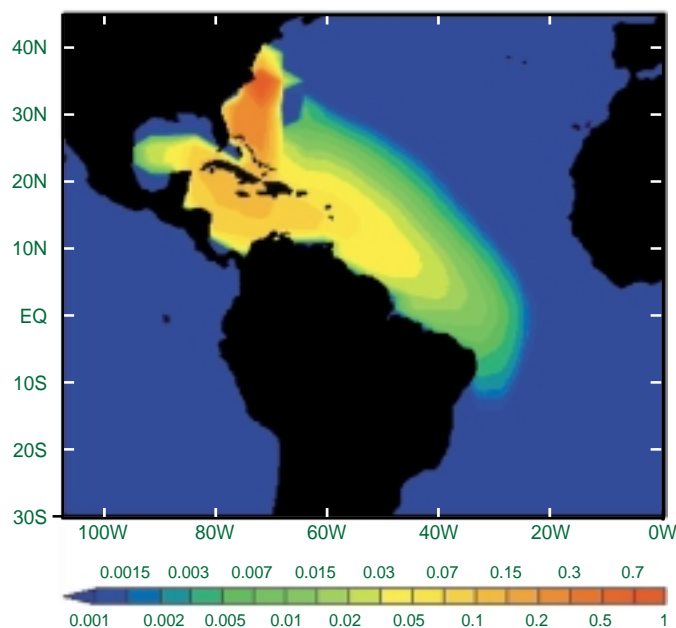


Fig. 3.4. Simulated distribution of carbon injected into the ocean at a depth of 1720 m off the coast of Cape Hatteras, North Carolina, after 20 years of continuous injection, as computed by the three-dimensional ocean model of Lawrence Livermore National Laboratory. At this depth, the model predicts that the carbon would be swept south with an undercurrent that flows beneath the Gulf Stream. This kind of simulation is necessary to determine the most effective depths and locations for deep-sea CO₂ injection.

ABB (Switzerland) have joined the project, which will continue through March 31, 2002. A field experiment will be performed in the summer of 2001 off the Kona Coast of Hawaii. The implementing research organizations are the Research Institute of Innovative Technology for the Earth (Japan), the Norwegian Institute for Water Research (Norway), the Institute of Ocean Sciences (Canada), and the Massachusetts Institute of Technology [(MIT) United States]. The general contractor for the project is the Pacific International Center for High-Technology Research in Hawaii. To investigate longer-term acute and chronic biological impacts, a phase 2 project may be conducted in an enclosure or at a semi-enclosed site

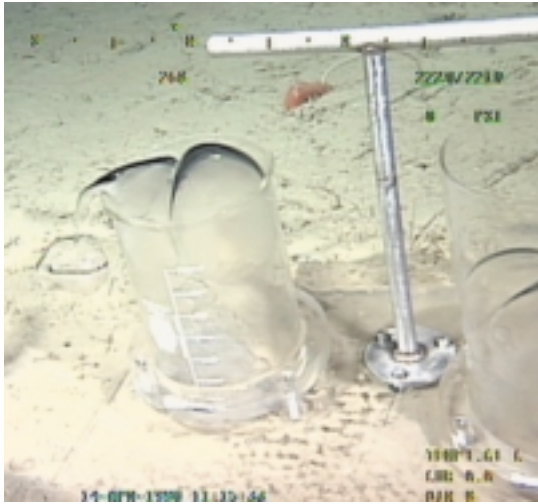
such as a fjord (Adams et al. 1998).

Experiments at the Monterey Bay Aquarium Research Institute (MBARI). In April 1998, MBARI scientists successfully carried out a controlled experiment with a 9-L liquid CO₂ release at a depth of 3650 m (in situ temperature about 1.6°C) from *Tiburon*, an unmanned, remotely operated vehicle (ROV) tethered to a ship. For several hours they observed the transformation of liquid CO₂ into solid hydrate (see sidebar).

Comparison of Ocean Carbon Cycle Models. The International Geosphere-Biosphere Programme initiated the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) in 1995 through the Global Analysis, Interpretation, and Modeling task force. OCMIP is an

international project devoted to improving marine carbon cycle models by comparing them with each other and by evaluating them using observational data sets. Thanks in part to some additional funding provided by the IEA Greenhouse Gas R&D Programme, the European research program on Global Ocean Storage and Anthropogenic Carbon will also look at global scientific aspects of the deep-ocean CO₂ sequestration issue. Specifically, the researchers will compare models of dispersion of CO₂ from seven hypothetical point sources to get a better understanding of sequestration efficiency. The U.S. component of OCMIP (funded by the National Science Foundation and the National Aeronautics and Space

Formation of CO₂ Hydrates in the Deep Sea



The accompanying photo from the MBARI experiment shows the overflow of liquid CO₂ onto the sea floor.

One suggested strategy for ocean sequestration of CO₂ by direct injection is to create a long-lived "CO₂ lake" on the ocean floor. To investigate this concept, a group of scientists at MBARI performed a series of deep ocean experiments for the disposal of fossil fuel CO₂ in the form of solid hydrate (CO₂ 5.75 H₂O). One recent experiment was carried out with the MBARI remotely operated vehicle (ROV) *Tiburon* off the central California coast. The ROV carried about 9 L of liquid CO₂ to a depth of 3650 m, where the pressure is

~36 MPa and the temperature is 1.6°C. The CO₂ was in a steel accumulator in which a piston continually adjusted to ambient pressure. The CO₂ was expelled by applying pressure on the piston from a water pump powered by vehicle hydraulics. Partly because CO₂ is denser than seawater at this depth, hydrate formation there dramatically differs from that observed at shallower depths.

MBARI scientists observed a rapid increase in the volume of the contained experiments as the CO₂-water interface rose, causing overflow of the liquid onto the sea floor about 100 min after the experiment started. They attributed this effect to the formation of a hydrate, readily seen as an accumulating mass at the bottom of the containers. This incorporation of large amounts of water in the solid phase resulted in an expansion of system volume by a factor of 4 to 7, causing the remaining liquid CO₂ to spill over. High interfacial tension maintained a strong barrier, preventing the released liquid CO₂ from interacting with the sediments (Brewer et al. 1999).

Administration and involving MIT, Pennsylvania State University, the National Center for Atmospheric Research, Lawrence Livermore National Laboratory, and Princeton University) is positioned to perform the same set of analyses with U.S. models, but no funding is available yet for this activity.

The CO₂ Ocean Sequestration Project in Japan. In April 1997, a 5-year national program looking at ocean sequestration of CO₂ began in Japan. Annual funding is in excess of \$10 million per year. The lead research institutes for this program are the

Research Institute of Innovative Technology for the Earth and the Kansai Environmental Engineering Center. This project encompasses joint research activities involving national institutes, private companies, and universities. The R&D agenda includes studying the behavior of liquid CO₂ released into the ocean, developing an engineering system for CO₂ injection, assessing the impacts of CO₂ on marine organisms, developing a near-field environmental impact assessment model, predicting the long-term fate of sequestered CO₂, and participating in the international field experiment (Masuda 1998).

3.1.3 Science and Technology Gaps

By comparing our technical capabilities with the technical requirements for developing effective, economical, and environmentally acceptable ocean sequestration technologies, we identified the following gaps:

- Insufficient information is available to optimize an injection strategy. For example, we must obtain answers to these questions:
 - Should dilute CO₂ streams be injected to try to avoid any environmental impacts? Will this strategy affect cost?
 - Should CO₂ streams be injected deep in the ocean to maximize retention time? Will it be worth the extra cost? Will the technical capability to do so be available by 2025?
- On the engineering side, these specific research gaps must be addressed:
 - Develop injection technology. Even though CO₂ can be injected now, we need a technology that is low in cost and maintenance and that can be used at greater ocean depths, if necessary.
 - Experimentally demonstrate the behavior of CO₂ near the injection point. This understanding may lead to injection strategies that can minimize any environmental impacts.
 - Better understand the dynamic response (i.e., kinetic behavior) corresponding to hydrate formation and dissolution. This is a first step in developing strategies that could use hydrate formation to our advantage for sequestering CO₂ (see Chap. 7).
 - Assuming no environmental constraints, develop strategies that maximize the neutralization of the acidified water by deep-ocean calcium carbonate sediments. This approach would have two positive effects: reducing pH changes in the water column and increasing the sequestration capacity of the ocean.
- Develop monitoring technology to observe changes in the ocean's biogeochemical processes and ecosystems.
- Concerning the effectiveness of injection technologies, some specific research gaps can be closed if researchers accomplish the following:
 - Address weaknesses in OGCMs, specifically western boundary currents, ocean bottom currents, and sub-grid scale processes (e.g., eddies); and test the models using natural and, perhaps, experimentally released tracers.
 - Couple near-field with far-field effects of CO₂ injection through a hierarchy of models (or nonuniform grids). Specifically, plume modeling should be coupled with basin- and global-scale ocean circulation models.
- Related to the environmental impacts of direct injection, some specific research gaps can be filled if researchers accomplish the following:
 - Understand the effects of the current oceanic uptake of CO₂. CO₂ goes into the ocean naturally, even with no enhancement or direct injection. These effects need to be understood.
 - Determine parameters for direct injection of CO₂ that will minimize environmental impacts.
 - Understand the effect of the sustained release of elevated levels of CO₂ on ocean biogeochemistry, ecosystems, and organisms. Are there any other

impacts that are important beyond the lowering of pH?

- Find answers to these questions: Should the injected CO₂ stream be pure (i.e., >99%)? Can ocean ecosystems tolerate other gases such as nitrogen, oxygen, hydrogen, CO, carbon oxysulfide, argon, hydrogen sulfide, NO_x, SO₂, and trace metals? To what levels? What effects would these gases have on ocean ecosystems?
- Investigate the impact of CO₂ on bioturbation of sediments. (Bioturbation is the disruption of marine sedimentary structures by the activities of benthic organisms.) Bioturbation makes skeletal calcium carbonate buried in the upper 10 or more centimeters of sediments available for the neutralization reaction of sequestered CO₂.

- Conduct an OGCM intercomparison exercise on point sources of CO₂ in the deep ocean with the goal of answering two questions: How good are the models? How can the models be improved?
- Support measurement programs that can provide validation data, including the results of better analyses of natural tracers.

- Conduct a pilot experiment to determine the feasibility of CO₂ injection, monitor its ecological impact, and characterize its far-field effects by collecting time-series data.
- Integrate the results of the previous efforts into specific injection scenarios (including recommended sites and modes of discharge) that optimize the tradeoffs among cost, environmental impacts, and effectiveness.

3.1.4 Research and Development Plan

To close the gaps, these specific line items are recommended for an R&D plan:

- Increase understanding of the behavior of CO₂ released in the ocean through laboratory studies, small-scale field experiments (e.g., the international field experiment and MBARI experiments) as well as near-field modeling efforts.
- Perform laboratory experiments to measure the effects of changes in pH and in CO₂ concentrations on organisms from mid-water and deep-sea habitats.
- Determine the environmental impacts of alternate scenarios (i.e., natural CO₂ uptake by the ocean).
- Improve global/regional modeling to quantify benefits and identify sites.

3.2 ENHANCEMENT OF NATURAL CARBON SEQUESTRATION IN THE OCEAN

The natural process of carbon fixation by phytoplankton (primary production) occurs at a rate of 50 Pg Cy⁻¹ and results in sequestration of carbon in the deep ocean via the biological pump (see Fig. 3.2). The biological pump involves the gravitational settling, slow remineralization, and burial of biogenic debris formed in the upper levels of the ocean. Phytoplankton in surface waters are rapidly grazed by zooplankton, which in turn may be consumed by larger animals such as fish. While it is estimated that 70–80% of the fixed carbon is recycled in surface waters (Sarmiento 1993), the rest is exported as particulate organic carbon (POC) to the deep ocean, where it is slowly mineralized by bacteria.

Fertilization of the oceans with micronutrients (such as iron) and macronutrients (such as nitrogen and phosphorus) is a strategy that is being considered to enhance drawdown of CO₂ from the atmosphere and thus accelerate the biological pump. Because certain areas of the ocean have low levels of phytoplankton yet a high concentration of nitrogen and phosphorus, it was realized that a lack of iron might limit phytoplankton growth (see the IRONEX sidebar) (Chisholm 1992). Initial short-term studies of iron fertilization in high-nutrient, low-chlorophyll (HNLC) waters have demonstrated that in situ fertilization of surface waters with iron to promote growth of phytoplankton is feasible at scales of tens of square kilometers (Coale et al. 1996).

Some commercial ventures are trying to capitalize on ocean fertilization for increasing their fish harvest. While

these ventures have a primary goal other than carbon sequestration, the strategies of fertilization and potential for environmental impact are similar, and all activities using fertilization to enhance fish production also claim carbon sequestration as a secondary benefit. For example, Ocean Farming, Inc., has planned a large-scale fertilization of the coastal waters of the Marshall Islands with iron, silicon, and phosphorus to increase the yield of tuna. This enterprise claims carbon sequestration as a secondary goal. Similarly, MARICULT, a European consortium of government and industry, is currently exploring the commercial feasibility of fertilizing coastal waters to increase the fish harvest. These commercial ventures are proceeding even though the potential ecological consequences of ocean fertilization are not yet known. Such consequences could range from changes in species diversity to

IRONEX: Iron Fertilization Experiments

The equatorial Pacific and Southern Oceans have excess macronutrients, nitrogen and phosphorus, in their surface waters. The late John Martin of Moss Landing Laboratories hypothesized that these nutrients are abundant in these regions because the micronutrient iron is very scarce, thus limiting phytoplankton growth. To test this hypothesis, two unenclosed transient iron fertilization experiments (IRONEX I and II) were conducted in the equatorial Pacific in 1993 and 1995, and a third experiment is being planned for the Southern Ocean. The results from IRONEX II, in which 500 kg iron was added to a 72 km² patch of surface water, were particularly dramatic. Quantum yield of photosynthesis increased significantly within 2 hours, nitrogen and phosphorus were drawn down, and chlorophyll concentrations increased 30-fold within a week, approaching levels typical of coastal waters. The species composition of the phytoplankton community shifted dramatically, with larger cells dominating by the end of the experiment. The bloom caused a decrease in the partial pressure of CO₂ in the middle of the patch and a three-fold increase in dimethyl sulfide production, both of which have implications for climate regulation. The duration of the experiment was 18 days—not long enough for significant changes at higher trophic levels—and the bloom dissipated shortly after the last injection of iron. It is not at all clear how sustained fertilization would affect ecosystem structure, export of carbon to the deep sea, and fluxes of greenhouse gases. These effects cannot be predicted from a transient experiment, so longer-term fertilization experiments are needed.

induction of anoxia and significant adverse effects on community structure and function. The fundamental question that should be answered is whether any alterations in the ocean ecosystem are justified relative to the benefits to society.

3.2.1 Science and Technology Requirements

An urgent need exists to determine the potential ecological consequences of large-scale ocean fertilization on the biosphere and on biogeochemical cycling. We need to be able to predict accurately how ecosystems will change in response to either short-term or sustained fertilization of the oceans. We also need to understand overall natural carbon sequestration efficiency in the oceans. Moreover, the feasibility of ocean fertilization will depend on optimization of fertilizer design, delivery, and ecological monitoring. Long-term ecological monitoring may prove extremely costly, so robust, dynamic models that predict ecosystem response will be the key to designing an economical and effective monitoring strategy.

3.2.2 Current Science and Technology Capabilities

Small-scale ocean fertilization is feasible from both an engineering and an economic perspective. The technology for fertilizing surface waters is fairly straightforward; it involves releasing microalgal nutrients such as iron, phosphorus, or nitrogen from platforms such as boats or airplanes. Recent iron fertilization experiments (IRONEX I and II) demonstrated that a deficiency of iron limits primary production (photosynthesis) in HNLC areas of the ocean where nitrogen and phosphorus are abundant (see the IRONEX

sidebar). The application of 500 kg of iron to 72 km² in the equatorial Pacific resulted in a 30-fold increase in phytoplankton biomass, a dramatic shift in species composition and elevated carbon fixation rates.

A number of technologies are available for monitoring ecosystem response to fertilization (or deliberate CO₂ injection), including assays for primary and secondary production using radiotracer techniques. Determining ecosystem response below the euphotic zone (the zone where the net rate of photosynthesis is positive) could use in situ filtration techniques that determine size distributions and chemistry of POC with minimal disturbance to the samples (Bishop et al. 1987; Bishop 1999) (see Fig. 3.5). To verify the effectiveness of sequestration, an ocean carbon inventory survey will use improved technologies to characterize the dissolved and particulate organic and inorganic carbon pools, rates of



Fig. 3.5. The multiple unit large-volume in situ filtration system (MULVFS) allows the precise determination of properties of particulate matter that is needed for a systematic survey of ocean carbon inventory and for the evaluation of ecosystem function. MULVFS samples are large enough to meet the diverse needs of multiple research groups.

transfer between carbon pools, and ecosystem function. More efficient shipboard sampling technologies for many key parameters have been developed or are under development. A growing suite of autonomously operating carbon and nutrient sensors is under development for deployment on moored, floating, or autonomous profiling platforms. The use of optical approaches for remote sensing of water column primary productivity and carbon biomass is rapidly progressing.

To simulate the effectiveness of ocean fertilization as a CO₂ sequestration strategy, two challenges must be met. First, we must be able to predict the change in biological carbon export from the surface ocean to the deep ocean as a result of ocean fertilization. Second, we must be able to predict the fate of this carbon after it reaches the deep ocean.

The problem of predicting changes in carbon export from the surface ocean resulting from fertilization is a difficult one, because it depends on hard-to-predict changes in ecosystem structure. Surface ocean biology models have simulated biological carbon export at specific locations reasonably well, but these models have generally been “tuned” to match some observations at these locations. Work is under way to try to develop a single model that can be applied across the global ocean to predict carbon export from physical and nutrient conditions alone. Although much progress has been made in this area, this goal has not yet been attained. It will be important to monitor closely any ocean fertilization experiments to develop solid data sets for use in evaluating ocean biology and ecosystem models.

Predicting the fate of biogenic carbon after it is transported to the deep ocean

is also a thorny problem. An important component of this prediction is the estimation of the depth at which the organic carbon will be oxidized, and this depth will depend on whether the organic carbon is particulate or dissolved, the size of the particles, and other factors. Once the organic carbon has oxidized in the deep ocean, the problem is largely equivalent to the deep-ocean CO₂ injection problem—predicting ocean transport, CO₂ degassing (returning to the atmosphere), and sediment interactions. Several simulations of this aspect of the problem have already been made using assumptions about the change in ocean biological carbon export and the depth of its oxidation. These studies have concluded that the effectiveness of ocean fertilization as a CO₂ sequestration strategy is very sensitive to the rate of ocean mixing between the ocean’s surface layers and its deep layers. If carbon in the deep layers is brought to the surface through mixing, then it could return to the atmosphere through degassing.

3.2.3 Science and Technology Gaps

A number of critical gaps exist in our understanding of ocean fertilization as a strategy for enhanced carbon sequestration.

- The impact of long-term ocean fertilization on the structure and function of marine ecosystems is unknown. Changes in phytoplankton structure are an inevitable consequence of fertilization, and this would lead to changes in ocean food web structure and dynamics. Such changes could have long-term (both positive and negative) impacts on fisheries, many of which are already declining primarily because of over-fishing. Fertilization with iron

and phosphorus in lake ecosystems selects for the growth of cyanobacteria over other types of phytoplankton; this proliferation could be a problem because certain species of cyanobacteria produce powerful toxins. While common marine cyanobacteria are non-toxic, further study is needed.

- The impact of sustained fertilization on the natural biogeochemical cycles in the ocean is completely unknown. The biogeochemical cycles of carbon, nitrogen, phosphorus, silicon, sulfur, cobalt, zinc, and perhaps selenium in marine environments are highly complex and intertwined, and recent evidence suggests that they are regulated by the availability of iron on a global scale. A perturbation of one elemental cycle can have repercussions that are unanticipated.
- The potential risk of fertilization leading to eutrophication must be determined. Eutrophication causes oxygen depletion, which could kill species that require oxygen; in some cases, it can lead to the production of methane by microorganisms. On the other hand, lack of oxygen in the sediments of the ocean floor could lead to an increase in the preservation of buried carbon due to slow rates of mineralization. The impact of fertilization on sediment-dwelling (benthic) organisms is unknown.
- At present, we do not have a good understanding of the effectiveness of ocean fertilization at a large scale. Will enhanced carbon fixation in surface waters result in an increase in carbon sequestered in the deep ocean? Some preliminary modeling work has been done, but these models are

based on simplified biological assumptions and have not been validated against real-world data.

3.2.4 Research and Development Plan

Sustained longer-term fertilization experiments are vitally important to assess the ecological consequences of in situ fertilization. Such experiments will also yield information that is vital to understanding the mechanisms that have triggered past climate changes such as glacial-interglacial transitions. We need to know how marine food webs change in response to nutrient enrichment. At a minimum, such research should seek to accomplish the following:

- Increase understanding of the existing “biological pump” and identify the nutrients (and micronutrients Fe, Zn, Co) that regulate it on a global scale. Naturally occurring fertilization by upwelling, wind-driven dust deposition, or iron-rich coastal runoff may provide insights into the role of nutrients in ocean sequestration of carbon.
- Determine to what extent increased primary production in surface waters enhances the biological pumping of carbon to deeper waters. This determination will require an inventory of ocean carbon, including export of POC and particulate inorganic carbon to the deep sea and the mineralization (oxidation) or dissolution of all carbon at depth. Development of technologies for autonomous determination of all forms of carbon is needed.
- Determine the impact of sequestration on biogeochemical cycling. For example, if carbon is sequestered, the available nitrogen

and phosphorus in surface waters will be reduced. How long will it take for natural nitrogen and phosphorus to be replenished to support ongoing primary production?

- Determine the relationship between iron and nitrogen fixation. Would fertilization with iron and phosphorus in the ocean cause cyanobacterial blooms that would increase the oceans' nitrogen inventory? Would an increase in nitrogen lead to an increase in carbon export?
- Monitor the effects of fertilization on phytoplankton community structure and trophic dynamics. Can nutrient ratios be "designed" to increase productivity without changing the community structure, thus minimizing environmental impacts?
- Validate models of sustained fertilization with improved biological parameterization. We need to couple physical, chemical, and biological models to predict the effectiveness of ocean sequestration. We especially need to know how long anthropogenic carbon will remain sequestered in the ocean.

3.3 LONGER-TERM, INNOVATIVE CONCEPTS FOR OCEAN CO₂ SEQUESTRATION

Whereas most of the research in ocean CO₂ sequestration has been in the areas of deep-sea CO₂ injection and ocean fertilization, both of these concepts are less than 25 years old, and a plan written 25 years ago might have missed these strategies. Therefore, we should encourage the development of innovative concepts for sequestering CO₂ in the oceans that may be the basis for advanced

technologies in the coming years and decades. A few concepts are described below for illustrative purposes only—at present we do not have enough information to judge their feasibility.

- **Converting concentrated CO₂ at a power plant to relatively strong carbonic acid, using the acid to dissolve carbonate minerals, and then releasing the dissolved carbonate and dissolved fossil-fuel CO₂ into the ocean.** This technique would greatly enhance ocean storage capacity and would eliminate concerns about changes in pH because the dissolved carbonate mineral would neutralize much of the acidity of the carbonic acid. This approach would greatly diminish eventual degassing back to the atmosphere, circumventing the need for pumping CO₂ to great distances and depths. Limitations of the concept include the need for large amounts of water and the need to transport more carbonate mineral than coal to the power plant.
- **Burial of organic carbon in the ocean.** Organic waste could be stored as a thick layer on the ocean bottom. Sources of this organic carbon could include farm waste, carbon-black from decarbonized fuel, or organic-rich dredged sediments. Biomass from fast-growing sea grasses, kelp forests, or terrestrial plants could be harvested for burial in the ocean. Transportation of large volumes of biomass to the ocean depths, however, may prove too costly. Moreover, anoxia and the production of methane may present a serious problem with this approach.

- **Mining hydroxides and bicarbonates (e.g., sodium hydroxide, potassium hydroxide, sodium bicarbonate) and dissolving them in the ocean.** These minerals, when dissolved, will neutralize the acidity produced by anthropogenic CO_2 and will effectively sequester that CO_2 in the oceans. The limited availability of these materials in nature may preclude this approach.

3.4 CONCLUSION

Because the ocean already is a large repository for carbon on the planet, it is not unreasonable to consider direct injection of CO_2 or enhancement of CO_2 fixation through fertilization as possible options for carbon sequestration. Technologies exist for direct injection of CO_2 at depth and for fertilization of the oceans with microalgal nutrients. However, we lack sufficient knowledge of the consequences of ocean sequestration on the biosphere and on natural biogeochemical cycling. Such knowledge is critical to responsible use of oceans as a carbon sequestration option. Long-

term studies on the impact of ocean sequestration on ecosystem dynamics and global biogeochemical cycling are needed (Fig. 3.6). The ocean plays an important role in sustaining the biosphere, so any change in ocean ecosystem function must be viewed with extreme caution.

Public perception of ocean sequestration will undoubtedly be an issue for its broader acceptability. Much of the public, as well as ocean advocacy groups, believe that the oceans must remain as pristine as possible. The fisheries industry will also be concerned about possible economic impacts resulting from ocean sequestration activities. Legal issues will undoubtedly be complicated. With the exception of the coastal economic zones, the ocean is international in domain and is protected by international treaties or agreements such as MARPOL or the Law of the Sea. Ultimately, both scientific understanding and public acceptability will determine whether ocean sequestration of carbon is a viable option.

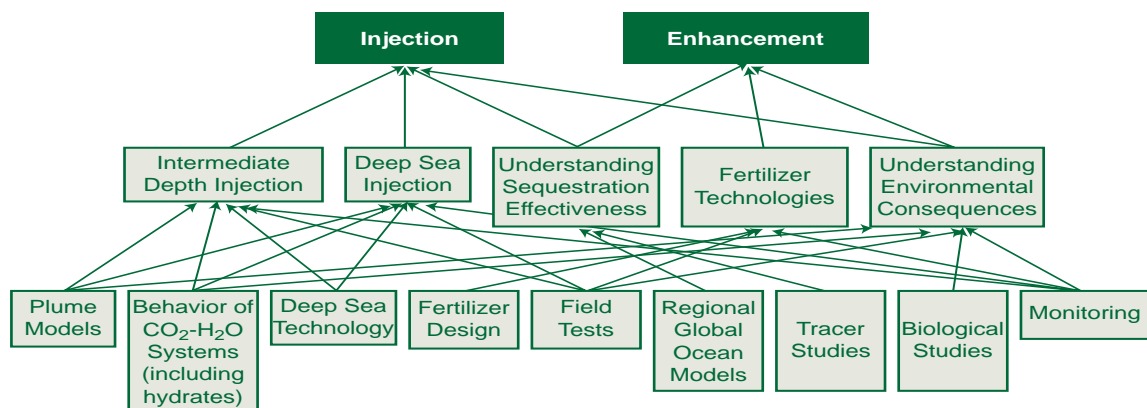


Fig. 3.6. R&D road map for ocean sequestration of CO_2 .

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